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More is less: agricultural impacts on the N cycle in Argentina

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Abstract. Human impact on nitrogen cycling, in particular the introduction of reactive nitrogen in terrestrial and aquatic ecosystems, can be examined at multiple scales, from the global impact on atmospheric chemistry to the impact of human activities on soil organic matter and fertility at the scale of square meters. Nevertheless, anthropogenic loading of nitrogen cycling in natural and managed ecosystems can be seen most directly at the regional scale, where concentrated human activity results in disruption of the nitrogen balance, with consequences for biogeochemical cycling and their interactions. Differences in land-use and agricultural practices between North and South America, and the importance of economic drivers that determine the fate of new reactive nitrogen demonstrate a contrasting picture of human impact on N cycling when the consequences are considered at the global vs. the regional scale. In particular, in the Pampa region of Argentina, the central agricultural zone of the country, the expansion of soybean cultivation in the last 20 years and the use of synthetic fertilizers have resulted in an influx of reactive nitrogen into these systems, with unexpected consequences for the nitrogen balance. A mass balance of nitrogen for soybean demonstrates that increased nitrogen inputs from biological fixation do not compensate for losses due to seed export, such that most areas under soybean cultivation are currently experiencing a substantive net loss of nitrogen. In addition, other crops that are currently being fertilized still show a net loss of nitrogen also due to the effect of primary exports from these agroecosystems. These simple models demonstrate that socioeconomic factors in large part drive the contrasting effects of anthropogenic impact on nitrogen cycling at global vs. regional scales. The future impact on nitrogen cycling in the Americas requires an integration of both ecological factors and socioeconomic drivers that will ultimately determine human disruption of the nitrogen cycle.

Introduction

The globalization of agriculture in the last century has resulted in marked changes in the movement of materials, goods and services at local, regional and global scales (Vitousek et al. 1997b). At present, estimates range from 20 to 30% of global net primary production (NPP) that is appropriated for human use, the vast majority stemming from agricultural practices (Vitousek et al.

1986; Rojstaczer et al. 2001; Imhoff et al. 2004). These patterns of appropriation are, however, region-specific with estimates for human consumption of net primary production in North America a much larger fraction than for South America (Imhoff et al. 2004). Beyond the biological import of agricultural practices affecting both managed and natural ecosystems, the importance of market and political forces driving changes in land use and manipulation of natural ecosystems for food production highlights the importance of understanding the socioeconomic framework of agriculture as a global change.

In particular, the increase in the use of nitrogen, both from synthetic fertilizers and by cropping of leguminous species has been estimated to have doubled the circulation of reactive nitrogen (e.g. Galloway and Cowling 2002; Galloway et al. 2004), with a consequent disruption of the N cycle and interaction with other biogeochemical cycles (Vitousek et al. 1997a; Austin et al. 2003). At the regional scale, anthropogenic loading of nitrogen from agriculture varies widely. For example, there are a number of differences in agricultural practices between North and South America, which largely stem from the use of synthetic fertilizer and the intensity of land use conversion in North America. Capital-intensive agriculture, which relies on large inputs of energy, machinery and synthetic fertilizers result in large outputs of inorganic nutrients to adjacent aquatic and estuarine systems (Howarth et al. 1996, 2002; Berman et al. 2005). However, the vast extent of land in the tropical zones of South America often have experienced a different land-use history, which includes slash-and-burn and conversion of forest ecosystems to transient agriculture, and low-input agriculture (Viglizzo et al. 1997a, b). As such, examining these impacts at a global scale may mask important contrasts with the effects of anthropogenic loading of nitrogen at regional or even local scales.

There is a general recognition that increased yields in the last 50 years have resulted in large part from the intensification of cereal crops, rather than the extensification of agriculture to marginal lands (Cassman 1999). It is estimated that agricultural intenstification will accelerate in the Latin American region in the next 50 years (Tilman et al. 2002). It has yet to be seen what the consequences will be for nitrogen loading in particular, as Latin American countries with substantial agricultural production such as Argentina and Brazil increase the use of fertilizers in an effort to meet food demand and maintain a competitive presence in the world agricultural market.

Current and future agricultural practices in Latin America are and will be critical in determining the human impact on the N cycle, due to the importance of the agricultural sector in the economies of most of the region (Martinelli et al. 2006, this volume). At the same time, differences both in climatic and edaphic properties as well as socioeconomic policies make generalization difficult in terms of predicting the consequences of human activity in this region. The objective of this review is to examine aspects of the impact of agriculture on nitrogen cycling in Argentina, principally the impact of soybean cultivation and synthetic fertilizer use, in an effort to understand the important vectors of human-induced global change on the N cycle at the regional scale and in a global context.

Agriculture in Argentina: the breadbasket of South America

Argentina is currently considered one of the major agricultural regions of the world, with most activity centered in the Pampa region of converted natural grasslands of Buenos Aires, Córdoba and Santa Fe provinces (Hall et al. 1992). This extensive region of 52 million hectares ranges in precipitation from more humid systems up to 1100 mm precipitation in the east to semiarid systems of 600 mm rainfall. Cereal grain agriculture began in the 1870s with rapid expansion until 1937, after which agriculture activity diminished. Mechanized agriculture grew in importance starting in the 1970s, but lagged behind other countries due to the access to technology and large-scale international capital (Viglizzo et al. 1997a, b). While land-use changes in the Pampa region are more recent, comparative analysis between North and South America suggest that the impact of agriculture has similar effects on carbon uptake and radiation capture in both continents (Guerschman and Paruelo 2005).

In the main agricultural region of Argentina, the Pampa, the major crops are in descending order of cultivated area, soybean (*Glycine max* (L.) Merr.), wheat (*Triticum aestivum* L.), maize (*Zea mays* L.) and sunflower (*Helianthus annuus* L.) (Figure 1, FAO 2004; SAGPyA 2005). While soybean is the crop with the most dedicated area in the region, there is very little nitrogen fertilizer used in this crop due to the large contribution of biological nitrogen

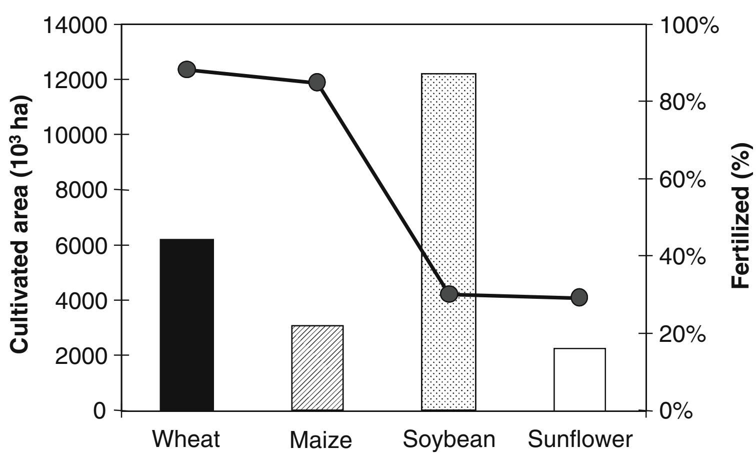

Figure 1. Cultivated area of major cereal crops and percentage of fertilizer use in the Pampa region of Argentina for 2002/2003. The bars represent the area cultivated for each crop; the line indicates that of the cropped area, what percentage is fertilized. Data from FAO (2004), Oliverio et al. (2004), SAGPyA (2005).

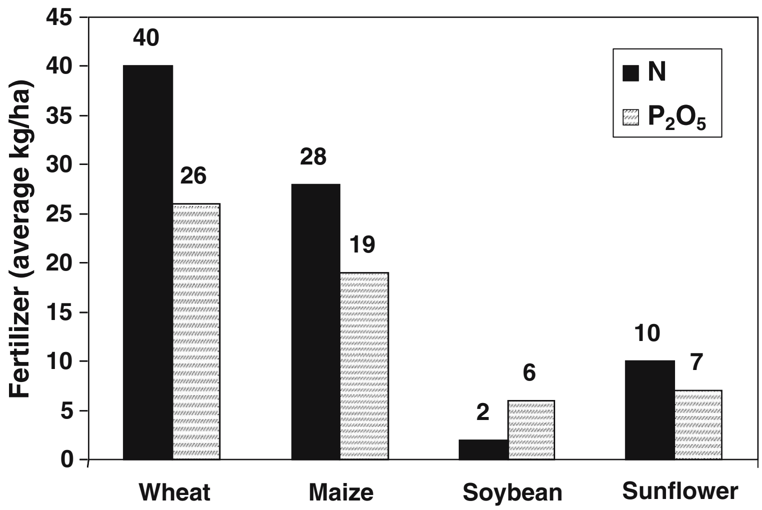

Figure 2. Average fertilizer use of nitrogen and phosphorus in the major cereal crops in the Pampa region of Argentina. Black bars represent synthetic N fertilizer (primarily urea) while striped bars represent phosphorus-based fertilizers. Data from (FAO 2004; Oliverio et al. 2004).

fixation (BNF) associated with its symbiosis with the bacteria *Rhizobium*. The minor application of nitrogen stems from the combined fertilizer use with diammonium phosphate. At the same time, synthetic fertilizer, almost exclusively in the form of urea, is now applied widely to both wheat and maize crops, and a large fraction of the area receives some fertilizer during the crop rotation (Figures 1 and 2). It is important to note that in almost all cases, the amount of nitrogen applied as fertilizer or gained through crop BNF is not sufficient to compensate for losses associated with current agricultural practices in the region (Viglizzo et al. 2001; Díaz-Zorita et al. 2002). We will address these two agriculture practices in the following sections, in an effort to examine the impact on nitrogen cycling and balance in the Pampa region.

More N from legumes? The case of soybean cultivation in Argentina

The expansion of cultivation of leguminous crops at the global scale is currently adding approximately 40 Tg of nitrogen annually, and is one of the principal pathways of reactive nitrogen entering terrestrial ecosystems (Vitousek et al. 1997a). This anthropogenic loading is especially relevant in Argentina, where both the expansion of soybean cropping in marginal land and the intensification of soybean cropping in currently cultivated land have increased markedly in the last 20 years (Figure 3).

In theory, legume-based cropping (or intercropping with other crops such as maize) can reduce carbon and nitrogen losses from cultivated land. The

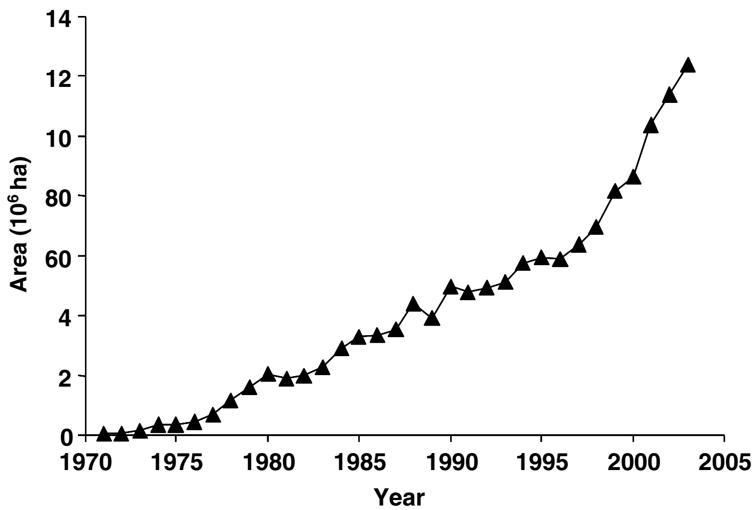

Figure 3. Area of soybean cultivation in Argentina, 1970–2004. Data from (SAGPyA 2005).

incorporation of low carbon:nitrogen litter in soil organic matter from leguminous crop residues, and timing of cropping has been shown to increase carbon and nitrogen retention in temperate agroecosystems (Drinkwater et al. 1998). In the region, areas dedicated to grazing by domestic livestock are frequently seeded with leguminous species such as alfalfa, which increase soil fertility and nitrogen retention (García-Perchác et al. 2004). In the case of crop species, however, the observed increase in soil C and N are compared to losses resulting from traditional cropping methods, generally single crop cultivation. The nitrogen balance from a cropping system must incorporate the various inputs and perhaps more importantly the outputs from the system in question. Our question focused on when natural ecosystems are converted to cropped systems, albeit with leguminous species, what is the effect on the net balance of nitrogen?

Soybean cultivation in Argentina has expanded markedly in the last 30 years in Argentina, with current estimates for 2004 of over more than 14,500,000 ha under cultivation (Figure 3), and the leading crop in the Pampa region (Figure 1). The introduction of glyphosate-tolerant soybean in Argentina, which was genetically modified for herbicide resistance, transformed the way in which this crop was cultivated, and over a very short time period. In 1996, glyphosate-tolerant soybean occupied less than 1% of the planted crop area; by 2002, over 90% of cultivated soybean was of the genetically modified strain, a rate of adoption that exceeded the United States (Trigo and Cap 2003). This was due, in part, to the release of patents on both the soybean seed source and the glysophosphate herbicide that resulted in rapid development of local varieties of glyphosate-tolerant soybean and relatively inexpensive access to the herbicide. A part of the technological package of planting of glyphosate-tolerant soybean was no-till cultivation, which increased in parallel with the expansion of soybean cultivation. As of 2002, over 90% of the area of soybean cultivation in the region is under no-till agricultural practices, with very low fertilizer inputs of both nitrogen and phosphorus (Figure 2).

We calculated a simple mass balance for nitrogen of a soybean crop based on the nitrogen content of the different plant compartments and biological nitrogen fixation, along a gradient of increasing grain yield from 2000 to 6000 kg/ha. We considered novel inputs for nitrogen only from biological fixation from the crop, while losses due to leaching, volatilization or topsoil erosion were not included in the calculations. Aboveground standing biomass was estimated based on grain yield (GY) and harvest index (HI–the ratio of grain biomass to aboveground biomass) from 53 studies from Argentina using local varieties of soybean (Dardanelli et al. 1991; Andrade 1995; Scheiner et al. 1997; Weilenmann de Tau and Lúquez 2000; Sadras and Calvino 2001; Di Ciocco et al. 2004). Our analysis showed that HI did not vary with grain yield ($HI = 1\times10^{-6}*GY + 0.3801$, $r^2 = 0.0012$, n.s.), which has also been shown in studies of soybean varieties from temperate North America (Schapaugh and Wilcox 1980). We assigned a mean value of 0.387 across the yield gradient based on the local studies. Soybean litter decomposed previously to the harvest, was set at 30% of aboveground standing biomass at harvest an upper bound for return of aboveground biomass to the soil. Data for root biomass was almost inexistent, but was estimated based on published studies of root to shoot ratio (root/aboveground biomass including seed), and we used the average value of 0.20 from these studies (Allmaras et al. 1975; Hudak and Patterson 1995; Scheiner et al. 1997).

Nitrogen concentration in soybean grain, aboveground biomass, litter and roots was estimated based on reported values of N content in each plant compartment from local studies and when data was not available, from other temperate ecosystems (Álvarez et al. 1995; Peoples 1995; Di Ciocco et al. 2004). Finally, the percentage of biological nitrogen fixation (BNF) was estimated for the crop as a whole, as well as the allocation to different plant compartments. We used a range of values from 20 to 50% of nitrogen in seed derived from BNF, based on ^{15}N isotpe pool dilution experiments from the region (Álvarez et al. 1995; Di Ciocco et al. 2004). We found no local studies that reported the fraction of BNF allocated to litter and roots, and as such, we estimated BNF in these compartments using simulated values of a widely used crop model in the region, CropGro.

With increasing crop yield, our model showed increasing amount of nitrogen derived from BNF, and increased return of nitrogen to the soil (Figure 4). Interestingly, a larger fraction of BNF was allocated to seed mass than other plant compartments (Álvarez et al. 1995; Di Ciocco et al. 2004) such that a larger fraction of the fixed N was destined for export. At the same time, increasing yield and N exports in grain estimated from the above data varied from 104 to 313 kg/ha (Figure 4). Across all yields, there was a net loss of nitrogen due to seed exports, with N deficits ranging from −42 to −126 kg/ha

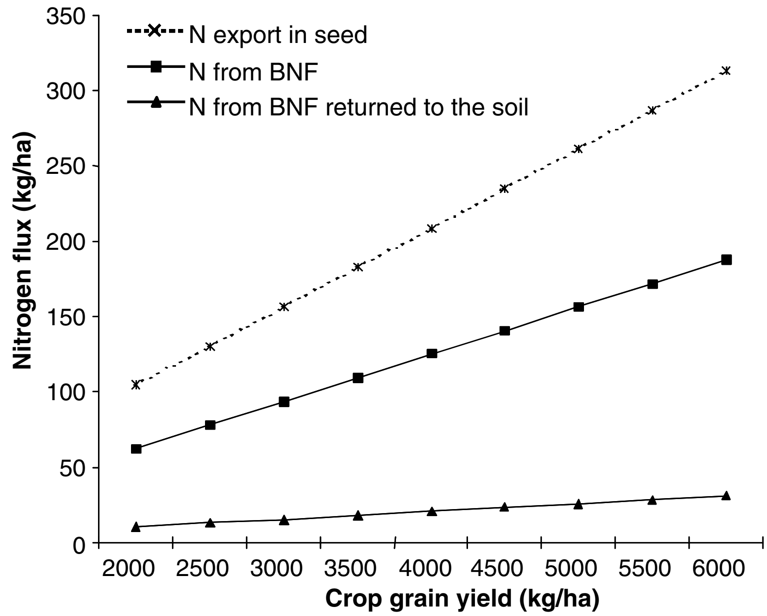

Figure 4. Mass balance of nitrogen for soybean cultivation in Argentina in a range of yields (2000–6000 kg/ha). Nitrogen inputs from fixation, N returned to soil and N exported in grain for different soybean yields (see text for details of model calculations).

(Figure 5), while the percentage of loss across all yields was 23% of the total crop N.

The potential for BNF of soybean varies from 0 to 95% (Unkovich and Pate 2000), and has been shown to vary inversely with soil nitrate concentration at

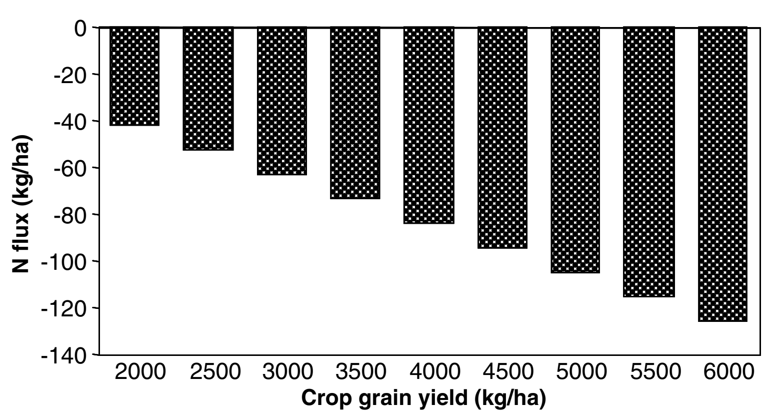

Figure 5. Net balance of ecosystem nitrogen with changes in soybean yield. Calculated deficit from nitrogen input from biological nitrogen fixation (BNF) minus nitrogen seed export.

sowing (Peoples 1995; Peoples et al. 1995; Singh et al. 2003). In addition, the BNF from soybean is reduced with moderate doses of fertilizer (Gan et al. 2002). Furthermore, studies from tropical or infertile soils typically show a much higher percentage of nitrogen in the soybean crop coming from BNF, which can be as high as 80% of biomass nitrogen (Maskey et al. 2001; Alves et al. 2003). The paradox of human impact of soybean cultivation on the nitrogen cycle in Argentina thus stems from the fact that these highly fertile soils may inhibit the capacity for nitrogen fixation, reducing the possible compensation of BNF for seed export of nitrogen. Application of N fertilizer works against the BNF efficiency, such that inorganic N amendments to the soil do not increase yield due to the inhibition of nodulation. Thus the current practice of single rotation soybean actually accentuates nitrogen losses due to the lack of economic and ecological motivation for adding nitrogenous fertilizer. Extrapolating these simple calculations to the Pampa region, for an average yield of 3000 kg/ha, this model estimates that total nitrogen losses from the region at 756,000 tons for 2002, not including possible losses due to leaching, volatilization, or soil erosion. Thus, in spite of a no-till cultivation and a leguminous crop, the example of soybean in Argentina demonstrates that human impact on the nitrogen cycle can result in a substantial net loss of nitrogen at the regional scale, and that current agricultural practices are essentially ‚mining' the nutrient capital of this region.

Why fertilize? The case of synthetic fertilizer use in Argentina

The development of the Haber–Bosch process in 1913 to synthetically produce nitrogen fertilizer revolutionized agriculture (Smil 2001; Galloway and Cowling 2002). A readily available source of nitrogenous fertilizer made it possible to increase yields in many crops, and was particularly important as a part of the technological package of the ‚green revolution' during the 1960s and 70s (Matson et al. 1997; Tilman et al. 2002). Globally, nitrogen fertilizer use has increased eight-fold in the last 50 years, and is expected to more than double by 2050 (Tilman et al. 2001). The increased use of nitrogen fertilizer globally has doubled food production in the last 35 years but coupled with increased yields have been adverse effects on adjacent downstream and natural ecosystems, including eutrophication of estuarine zones (Rabalais et al. 1996; Howarth et al. 2002). At the same time, there is great deal of regional variation within Latin America in the intensity of nitrogen fertilizer use, with Argentina being on the lower end of the range of fertilizer application (Figure 6a). Because of the highly fertile Pampa soils, however, Argentina has a fertilizer efficiency (kg grain/kg fertilizer applied) that is one of the highest in the world (Figure 6b).

Outside of North America and Europe, ecological consequences of nitrogen use in agriculture have been less evident. Nevertheless, intensive agricultural practices in the Yaqui Valley of México, have resulted in extensive phytoplankton blooms in nitrogen-limited areas of the Pacific Ocean very recently

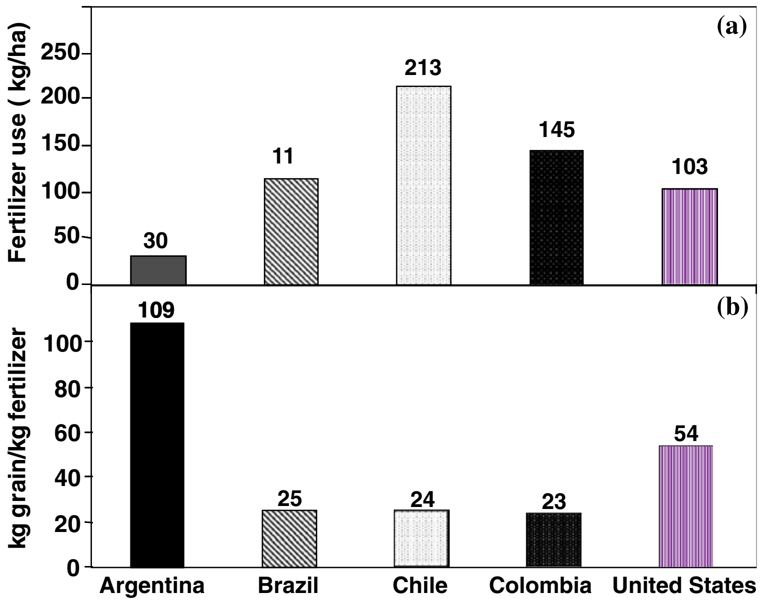

Figure 6. Fertilizer use and fertilizer use efficiency in Argentina and other selected countries of the Americas. A) Total fertilizer use per hectare of arable land and B) grain produced per kilogram of fertilizer applied (Data from FAO 2002).

(Berman et al. 2005). In general, the use of fertilizers in agriculture in South America and in particular in Argentina, has had a much shorter history than North America and Europe. It was not until the 1970s with the introduction of improved crop varieties that the benefits of nitrogen fertilizer could be seen and hence promoted the practice of fertilizer application. In Argentina, the introduction of a government-subsidized credit plan in 1973 that allowed the purchase of fertilizers against future profits from the harvested crop resulted in the growing use of urea, and a stabilization of the relationship in prices between fertilizers and wheat and corn. Much more important for fertilizer use in agriculture, however, was the election of a government in 1989 which was based on a free market economy and open trade policies (Trigo and Cap 2003).

Two consequences of government policy had a large impact on the increase in the use of fertilizers between 1992 and 2001 (Figure 7). The first was the removal of the export tax, which caused a large increase in the profit margin for agricultural exports and an incentive for higher yields. Second, the ‚stabilization' of the Argentine currency by linking it 1:1 with the dollar made it possible to purchase previously unavailable products such as fertilizer and herbicides. The resulting change in the political administration caused a dramatic increase in fertilizer application until 2001, almost entirely from imported sources (Figure 8). After the severe economic crisis of 2001–2002 and the devaluation of the Argentinean peso, the national production of fertilizers increased drastically, to the point where Argentina now is an exporter of

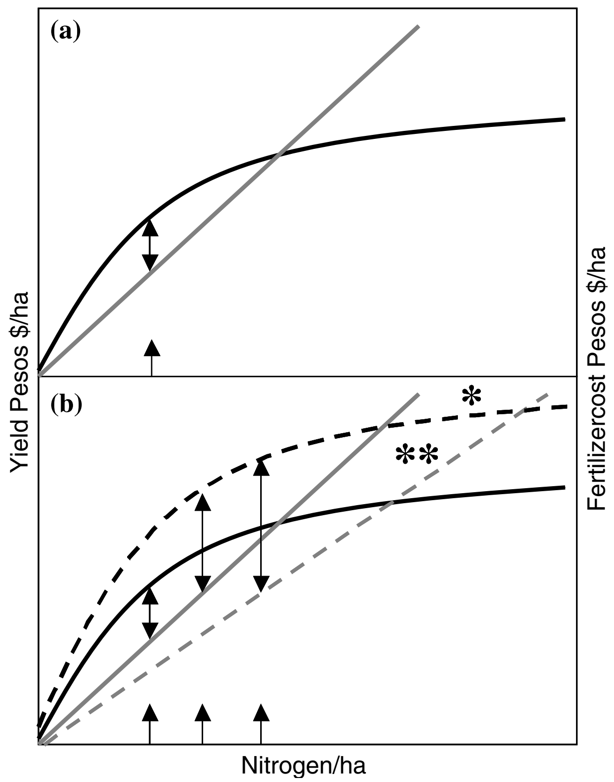

Figure 7. Conceptual diagram of how economic policies in Argentina altered fertilizer use since 1989. A) Simple model of diminishing returns on yield with application of nitrogen fertilizer in a static economic situation. The choice of fertilizer dose, marked with the arrow, is made based on the maximum difference between fertilizer cost and change in yield. B) The removal of the export tax (*) increased the value of the harvested crop, shifting the yield curve upward, and the stability and convertibility of the peso (**) resulted in a decrease in the real cost of fertilizer. The net result is a strong economic incentive to increase fertilizer use as the dose for maximum profit is shifted to the right on the axis of fertilization (marked with arrows).

fertilizers (Figure 8). This trend of increased fertilizer use has been observed in other parts of Latin America, particularly in Brazil, where similar changes in government policy have stimulated economic growth in the agricultural sector (Martinelli et al. 2006, but see Baisre 2006, this volume).

The increased use of nitrogen fertilizer has not compensated for the export of elements in grain from all cropping systems. Analysis of agricultural impact in the last century suggests that low-input agriculture has reduced the nitrogen capital of the Pampa region (Viglizzo et al. 1997a, b), but estimates with current fertilization rates also demonstrate a net loss of N, P, K and S in all major crops (Figure 9, García et al. 2005). In particular, the net balance of nitrogen use in the Pampa region of Argentina for 2002 ranges from 25 to 100 kg/ha deficit of N in this region, due to the export of nitrogen in grain and seed

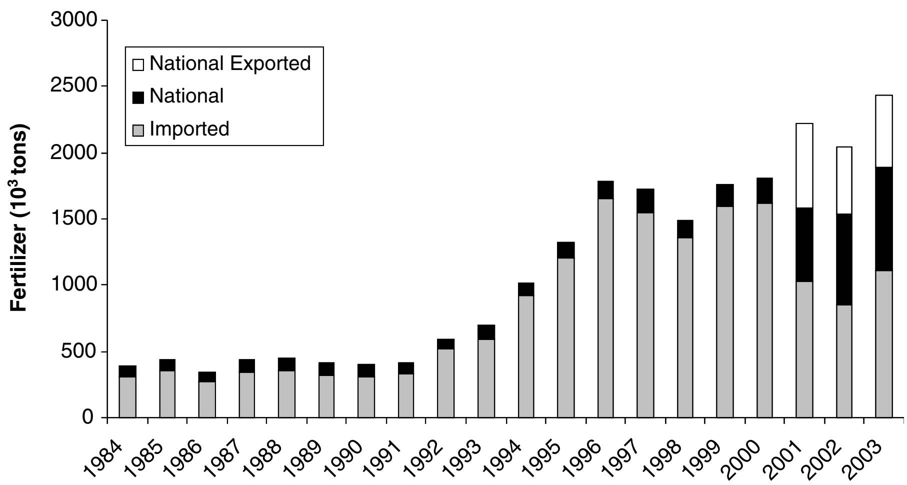

Figure 8. Synthetic fertilizer use in Argentina, 1984–2003, from national and imported sources. Data from (Conde Prat and De Simone 2004 ; Oliverio et al. 2004; SACPyA 2005).

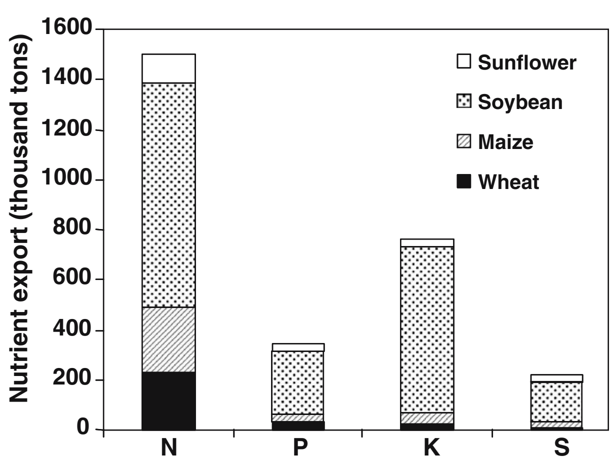

Figure 9. Nutrient losses (N, P, K and S) from the Pampa region of Argentina, based on calculations of fertilizer application and grain export. Source: García et al. (2005) and http://www.inpofos.org.

(Figure 10, García et al. 2005). Again, the relative low input of fertilizer use in this region and the high fertility of the soils results in an export of nutrient capital, and a negative balance for the region, not only for nitrogen but for other elements as well.

It is clear from these two examples of the effect of agricultural practices on nitrogen cycling in Argentina that understanding the present and future human impact on N cycling must include the effects of political and economic policies

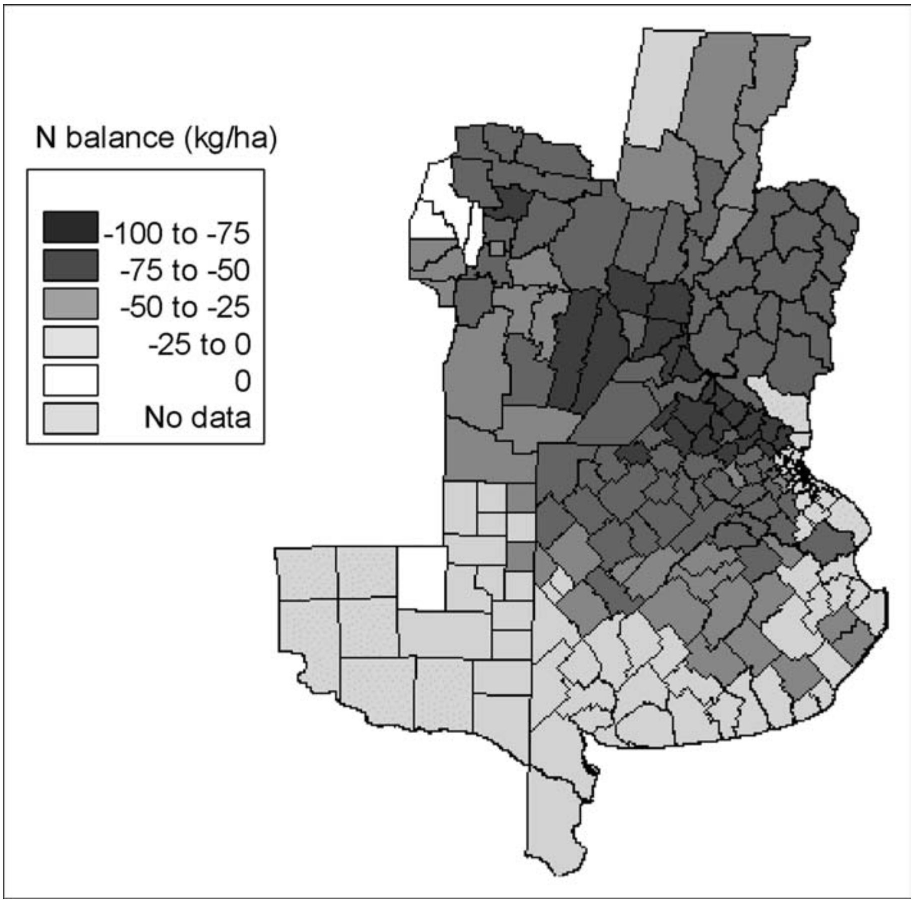

Figure 10. Spatially explicit nitrogen balance in the Argentinean Pampa, 2003 Source: García et al. (2005) and http://www.inpofos.org.

on nitrogen use, cycling and movement across regional boundaries, both in developed and developing economies. In addition, the challenge of integrating global and regional effects of anthropogenic N loading will require region-specific responses due to the dynamic political and economic environment of much of Latin America. Most regions of the northern hemisphere such as Canada and the United States continue to increase the amount of reactive nitrogen in the form of agricultural inputs (Schindler et al. 2006, this volume), while other regions, such as Cuba, have followed a different trajectory of decreasing nitrogen inputs, due to elimination of fertilizer subsidies (Baisre 2006, this volume). Argentina, with its rapid changes in free-market economic policies in the last 20 years coupled with the importance of the agricultural sector serves as an example of a hybrid between the importance of economic and ecological drivers affecting human impact on nitrogen cycling. The central conclusion for Argentina is that in spite of increased cultivation with leguminous crops and a small but dramatic increase in nitrogen fertilizer use, the net effect on N cycling for this region is **negative**, with reductions in N in soil organic matter and net loss of nitrogen from these agroecosystems. These models reinforce other analyses from the region, such that the challenge is to find a crop rotation that combines high BNF efficiency with lower nitrogen losses to begin to compensate for the current negative balance of soybean cultivation (Diaz Zorita and Duarte 2004). These losses, however, are likely to increase in the next 15 years due to growing demand for cereal grain production and the stated goal of 100 million metric tonnes of cereal production in Argentina. The dynamic nature of political change and socioeconomic drivers affecting agricultural practices must be incorporated into our understanding of the consequences of human activity on nitrogen cycling at all scales.

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